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APPLICATION OF A STRUCTURAL OPTIMIZATION PROCEDURE FOR ADVANCED--ETC(U)
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Application of a Structural Optimization Procedure for Advanced Wings

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6 # APPLICATION OF A STRUCTURAL OPTIMIZATION PROCEDURE FOR ADVANCED WINGS

by

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Paper presented at the 51st Meeting of the AGARD Structures and Materials Panel
held in Aix-en-Provence, France on 14–19 September 1980.

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PREFACE

During its Meeting in Aix-en-Provence, in Fall 1980, a paper was presented by Mr H.Gödel to the Sub-Committee on Aeroelasticity of the Structures and Materials Panel on the use of structural optimization methods to obtain practical minimum-weight designs which meet the constraints of loads, stresses, buckling, deflections, divergence and flutter. Impressive results were exhibited.

The excellent presentation of this advanced application of optimization procedures was welcomed by the Sub-Committee as being a very important contribution to its activities in Aeroelasticity. Its publication as an AGARD Report will help dissemination of new methods and techniques amongst the NATO community.

G.COUPRY
Chairman, Sub-Committee
on Aeroelasticity

APPLICATION OF A STRUCTURAL OPTIMIZATION PROCEDURE FOR ADVANCED WINGS

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SUMMARY

A computer software system called ASAT exists at MBB which allows an automatic design of minimum weight structures. In this paper, the application of this system to several structures is described.

It is shown that a structural optimization system can be very useful in the preliminary design of an airplane, especially when it consists of several modules such as static load calculation, deformations and stress calculation by finite elements, static aeroelastics, weight calculation, unsteady aerodynamic forces, vibration calculation, flutter calculation, flutter and strength optimization which all can be used separately and independently.

INTRODUCTION

For structural design of modern airplanes, the use of an optimization computer program is mandatory in order to achieve a minimum weight structure whilst taking into account both strength and aeroelastic requirements.

During a cooperation program /1/ with the U.S. Air Force Flight Dynamics Laboratory, the MBB company exchanged several computer programs in return for receiving the FASTOP-computer-system /2/. This exchange took place in 1977, and for the last three years, the structural dynamic group of MBB has further refined the program and also added a static aeroelastic part to it. This new system is now called ASAT. (Automatische Struktur-Auslegung für Tragflächen). This paper deals with the application of ASAT.

Several structural examples are treated in this paper:

- A simplified structure to show the capabilities of the system (the analysis of this structure was partly sponsored by the ZTL-Research Program of the German Ministry of Defense).
- Aeroelastic efficiency calcs for fin and rudder.
- Structural layout of a carbon fibre composite Delta wing.

TECHNICAL APPROACH

The ASAT-program is able to size cantilevered or free-free surface structures for flutter speed or strength constraints. It is based on a finite element method. Buckling of elements is considered. Also minimum skin gauges can be a limiting factor for sizing. The aeroelastic efficiencies are calculated directly by using the aerodynamic influence coefficients - no iteration procedure is applied. The mathematical approach can be found in /3/ and /4/.

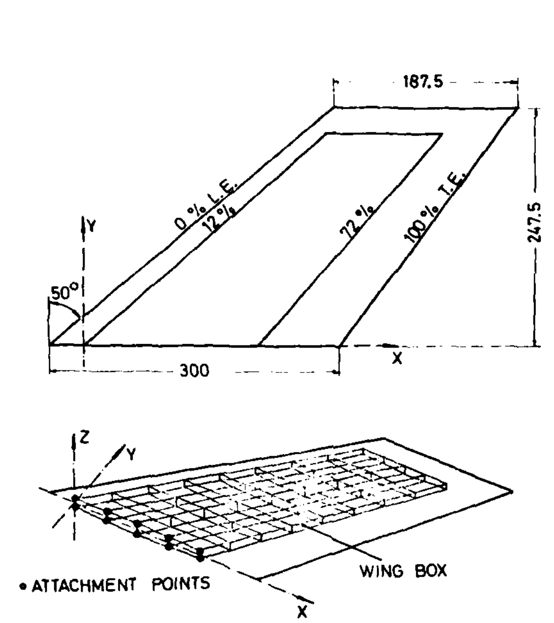
SIZING OF A SIMPLIFIED METAL WING STRUCTURE FOR STRENGTH AND FLUTTER CONSTRAINTS

In order to try out the computer system, a simplified structural model was chosen (Fig. 1). The thickness to chord ratio is constant 5 %. The surface is cantilevered.

The conditions which are sizing the skin thickness against buckling are presented in Fig. 2. Two aerodynamic load cases were defined:

Load case 1: $Ma = 0.9$, $q = 5.52 \frac{N}{cm^2}$, $\alpha = 8°$

Load case 2: $Ma = 1.4$, $q = 8.28 \frac{N}{cm^2}$, $\alpha = 5.5°$



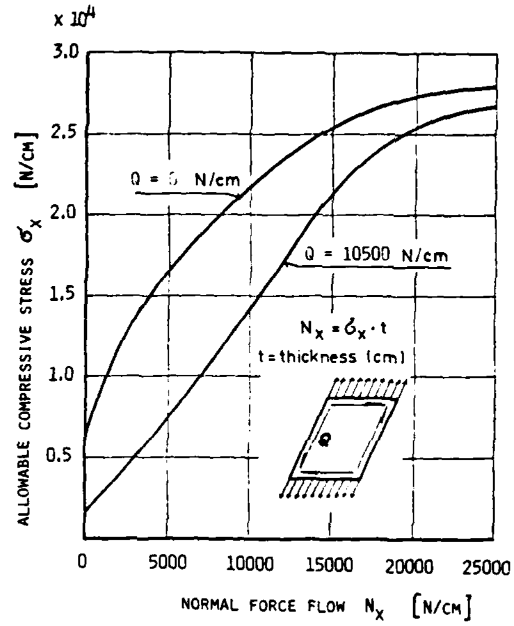
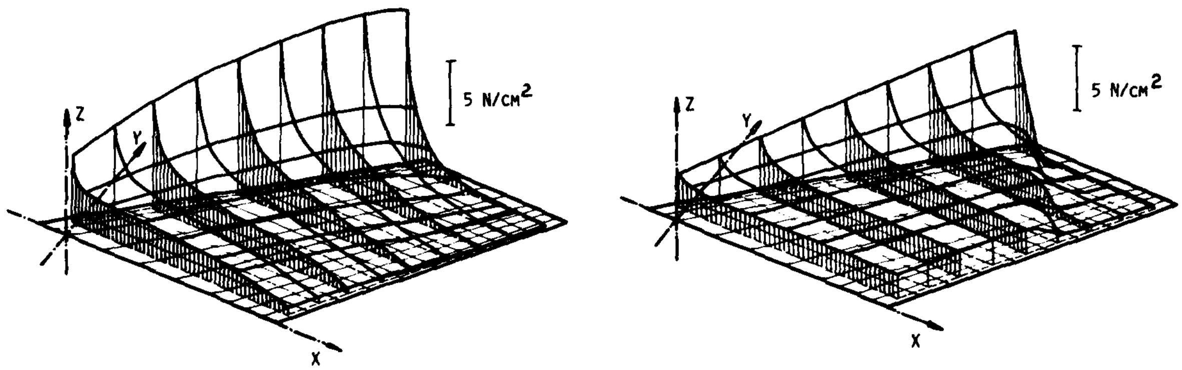


Fig. 1 GEOMETRY AND STRUCTURAL IDEALIZATION

Fig. 2 ALLOWABLE COMPRESSIVE STRESS σ_x AS FUNCTION OF NORMAL FORCE FLOW N_x AND SHEAR FLOW Q

The stationary pressure distributions as calculated by the computer program are shown in Fig. 3. A transformation procedure is implemented which transfers the aerodynamic loads from the panel center to the structural grid points.



LOAD CASE 1: MA= 0.9, Q= 5.52 N/CM^2, α = 8°

LOAD CASE 2: MA= 1.4, Q= 8.28 N/CM^2, α = 5.5°

Fig. 3 STATIONARY PRESSURE DISTRIBUTIONS

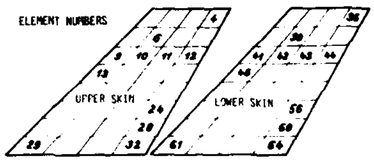
The optimization process is explained best by Table 1 and 2.

Thicknesses and flutter derivatives for characteristical structural elements for the upper and lower skin are printed for successive steps of the optimization procedure. Initially, a constant skin thickness is provided. After three steps of the SOP-module (Struktur OPtimierung) a fully stressed design is reached where the last weight change is only 0.7 kg. This is plotted in Table 1.

Weight	Initial weight for constant skin thickness	Iteration Step 1	2	3
kg	51.4	56.7	55.0	54.3

TABLE 1 Weight for structural optimization procedure (SOP)

In Table 2, the iteration procedure is shown for selected structural elements. It starts with the skin thicknesses of step 3 of SOP and then it iterates between FOP (Flatter OPtimierung) to fulfill the required flutter speed with a minimum weight increase and still keeps the fully stressed design by running through SOP.



UPPER COVER SKIN

THICKNESS mm

Element	Start Value	SOP	FOP	SOP	FOP	SOP	FOP	SOP	FOP	SOP	FOP
4	2.00	0.76	0.76	0.76	0.96	0.96	0.99	0.99	0.96	0.96	0.96
6	2.00	2.78	2.73	2.64	2.63	2.58	2.58	2.56	2.56	2.56	2.56
9	2.00	1.58	1.91	1.91	2.96	2.96	3.73	3.73	3.95	3.95	3.95
10	2.00	2.46	2.34	2.62	2.95	2.95	3.12	3.12	2.97	2.95	2.95
11	2.00	1.72	1.76	1.85	2.72	2.72	3.43	3.43	3.69	3.69	3.69
12	2.00	2.13	2.17	2.29	3.05	3.05	3.53	3.53	3.51	3.51	3.51
13	2.00	2.18	2.28	2.52	3.13	3.13	3.20	3.20	3.13	3.13	3.13
24	2.00	5.84	5.89	5.88	5.88	5.87	5.86	5.85	5.85	5.85	5.85
28	2.00	5.39	5.59	5.47	5.47	5.30	5.23	5.16	5.13	5.12	5.12
29	2.00	1.67	1.54	1.53	1.54	1.60	1.64	1.67	1.69	1.69	1.69
32	2.00	7.82	8.00	7.94	7.94	7.81	7.76	7.70	7.68	7.68	7.68

FLUTTER VELOCITY DERIVATIVES kts/kg

Element	FOP	FOP	FOP	FOP	FOP
4	10.38	13.41	11.09	10.92	11.30
6	2,52	4.09	5.32	5.60	5.58
9	17.82	20.50	16.42	13.79	13.16
10	7.92	10.85	11.56	10.85	10.97
11	12.92	18.47	16.49	14.14	13.58
12	10.39	15.23	13.78	12.13	12.08
13	13.46	13.22	10.79	10.32	10.23
24	0.27	0.62	1.13	1.32	1.32
28	-0.29	-0.15	0.14	0.26	0.27
29	0.90	1.58	2.29	2.51	2.46
32	-0.50	-0.46	-0.34	-0.29	-0.28

LOWER COVER SKIN

THICKNFSS mm

Element	Start Value	SOP	FOP	SOP	FOP	SOP	FOP	SOP	FOP	SOP	FOP
36	2.00	0.76	0.76	0.76	0.96	0.96	0.99	0.99	0.96	0.96	0.96
38	2.00	0.79	0.80	0.80	0.98	0.98	0.98	0.98	0.98	0.98	0.98
41	2.00	0.76	2.17	2.17	3.92	3.92	4.55	4.55	4.45	4.45	4.45
42	2.00	0.79	1.59	1.59	2.78	2.78	3.38	3.38	3.46	3.46	3.46
43	2.00	0.76	1.84	1.84	3.37	3.37	4.07	4.07	4.14	4.14	4.14
44	2.00	0.76	1.53	1.53	2.73	2.73	3.30	3.30	3.35	3.35	.35
45	2.00	0.80	1.94	1.94	2.87	2.87	3.08	3.08	2.95	2.95	.95
56	2.00	3.01	3.10	3.02	3.00	2.88	2.85	2.82	2.81	2.81	2.81
60	2.00	2.84	2.97	2.91	.90	2.78	2.73	2.69	2.67	2.67	2.67
61	2.00	0.76	0.76	0.76	0.77	0.77	0.82	0.82	0.81	0.81	0.81
64	2.00	4.55	4.43	4.64	4.63	4.51	4.47	4.42	4.40	4.40	4.40

FLUTTER VELOCITY DERIVATIVES kts/kg

Element	FOP	FOP	FOP	FOP	FOP
36	10.19	13.61	10.98	10.96	11.29
38	12.37	12.82	9.96	9.42	9.14
41	100.04	27.81	13.92	11.74	12.23
42	50.07	26.09	15.30	12.85	12.63
43	72.06	28.60	15.03	12.68	12.55
44	49.40	27.31	15.09	12.69	12.49
45	72.78	18.68	11.87	11.30	12.01
56	1.93	2.91	4.10	4.42	4.41
60	-1.01	-0.24	0.96	1.36	1.35
61	6.37	8.82	11.57	12.03	12.16
64	-1.25	-1.11	-0.81	-0.66	-0.63

FINAL ST'UCTURAL WEIGHT 64.6 kg

TABLE 2 Optimization Progress for selected structural elements

The elements most important for flutter speed (stiffness change) are underlined. It is interesting to note that for instance the upper skin is mostly designed by strength requirements whereas the lower skin thickness can be used to raise the flutter speed by a stiffness change. After a constant flutter derivative for each important flutter element is reached then the process is finished. Graphically, this is shown in Fig. 4.

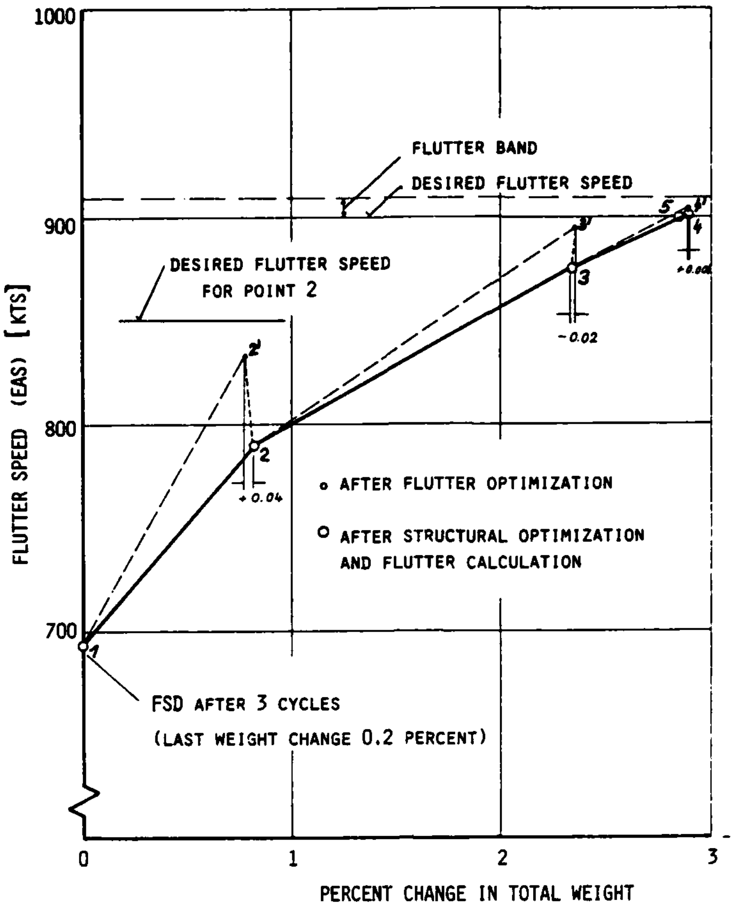


Fig. 4 RESULTS OF REDESIGN STUDY

A flutter speed is calculated for the initial fully stressed design (FSD) being 700 kts. After five iteration steps, the desired flutter speed of 900 kts is reached with an increase of less than 3 % of total weight. The loss of flutter speed from 2' to 2 and 3' to 3 can be explained this way: The program uses the old vibration modes to get from 1 to 2', but these modes change a little which is reflected in point 2. When the structural changes are smaller and smaller then the modes stay practically the same (see point 4', 4 and 5). In Fig. 5, the elastic deformations before and after optimization are shown.

In Fig. 6, the vibration mode shapes are depicted. From this picture, it can be seen that the mode shapes stay almost the same, and only the frequencies are changed.

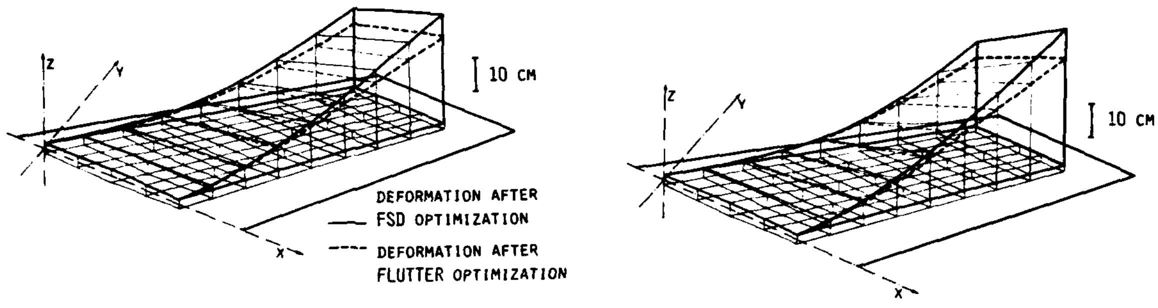


FIG. 5 DEFORMATION OF THE STRUCTURE DUE TO LOAD CASE 1 AND 2

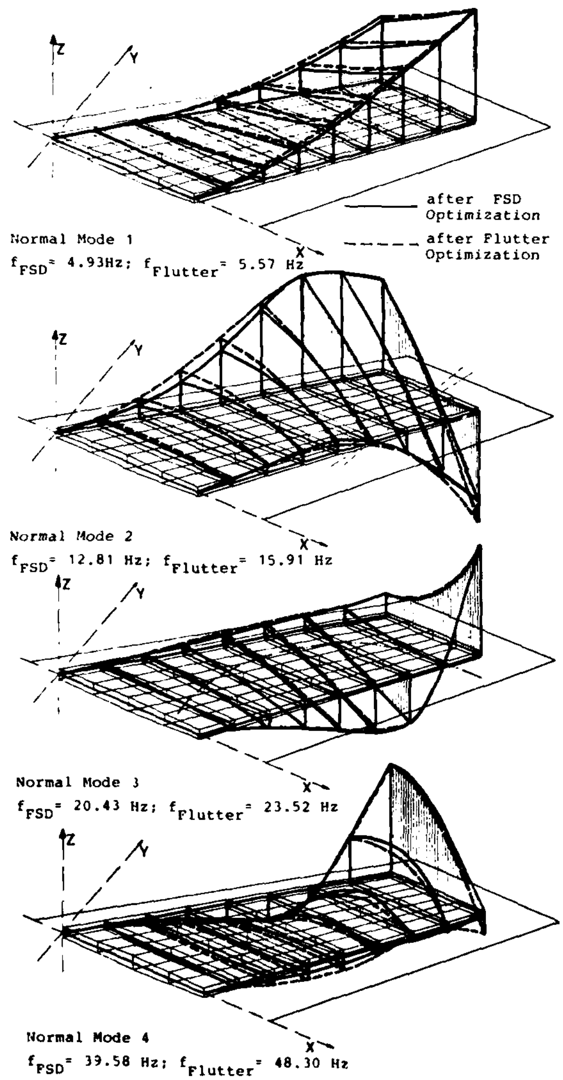


FIG. 6 NORMAL MODES, CALCULATED AFTER INITIAL FSD AND AFTER FLUTTER OPTIMIZATION

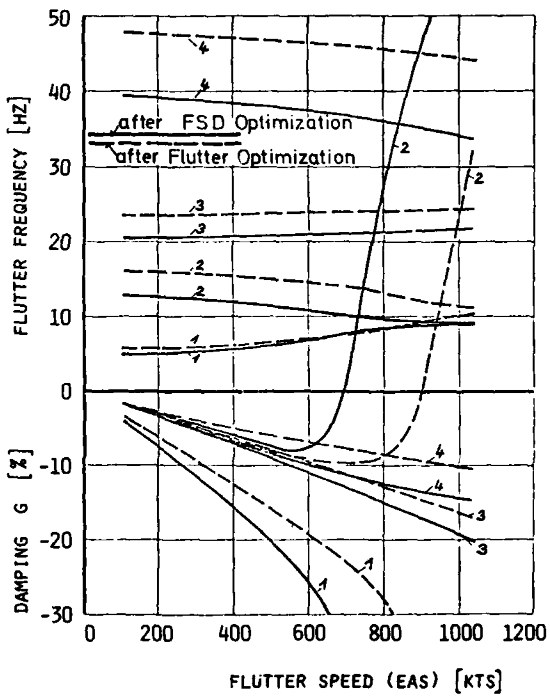


FIG. 7 RESULTS OF FLUTTER ANALYSIS

The flutter speed increase stems mainly from the frequency separation of mode 1 (bending) and mode 2 (torsion) as shown in Fig. 7.

The program FOP has also the possibility to increase flutter speed by mass balancing. Seven mass positions at the outer wing to apply balance masses were provided but the flutter derivatives were so small that this possibility was neglected automatically.

The final results are presented in Fig. 8 and 9 as skin thicknesses for the upper and lower skin before and after optimization. Also the stress ratios - which should be unity when fully stressed - and the flutter derivatives are shown.

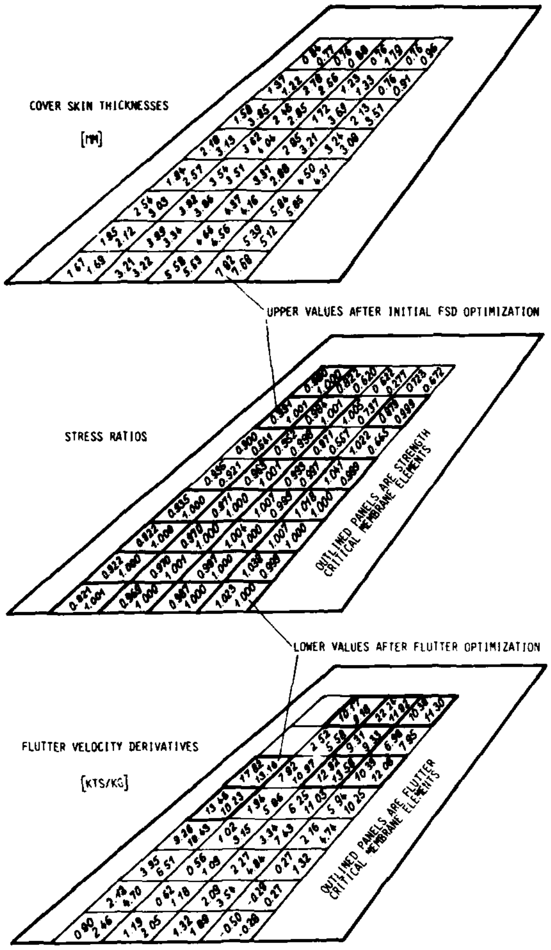


FIG. 8 REDESIGN RESULTS FOR UPPER COVER SKIN

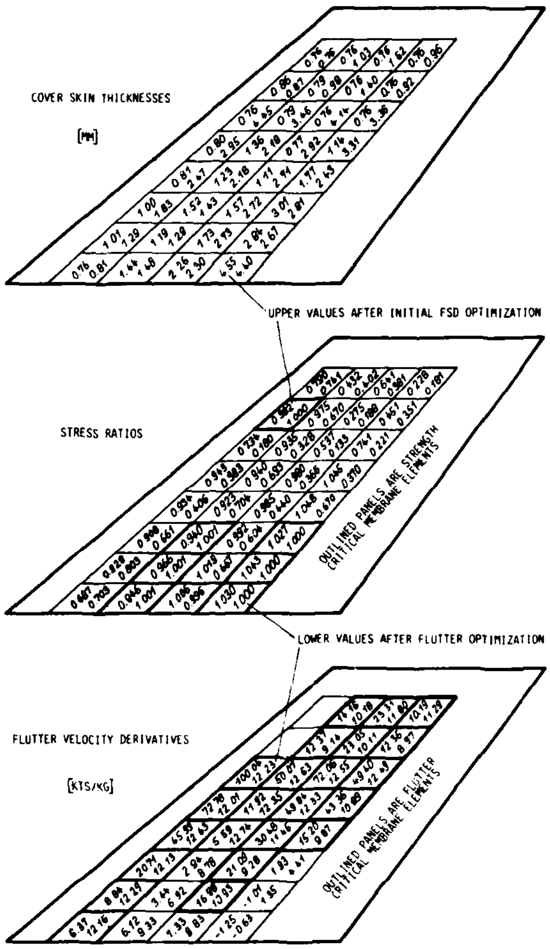


FIG. 9 REDESIGN RESULTS FOR LOWER COVER SKIN

The normal force flow for load case 2 is shown in Fig. 10 as a typical example of the strength calculation.

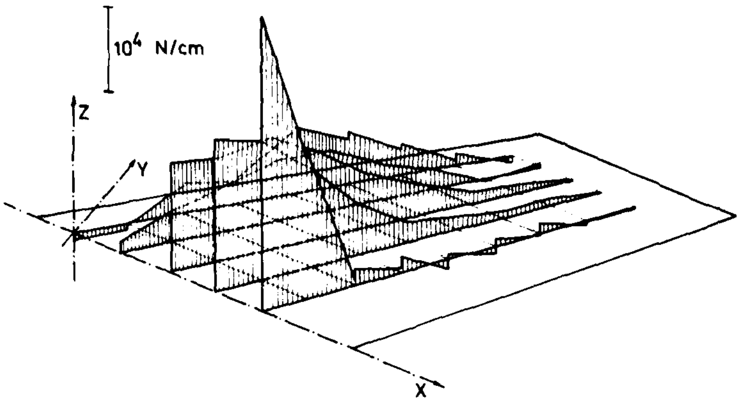


Fig. 10 NORMAL FORCE FLOW IN SPAR DIRECTION FOR LOAD CASE 2

Comparisons for stress calculations with different elements are presented in Fig.11. This figure proves that with a relative crude element and mesh system good correlation with analyses using more sophisticated elements - such as NASTRAN (triangular membrane with linearly varying stress) - can be achieved. This is an important result because the cruder the idealization can be, the less computer time is needed to run the optimization program.

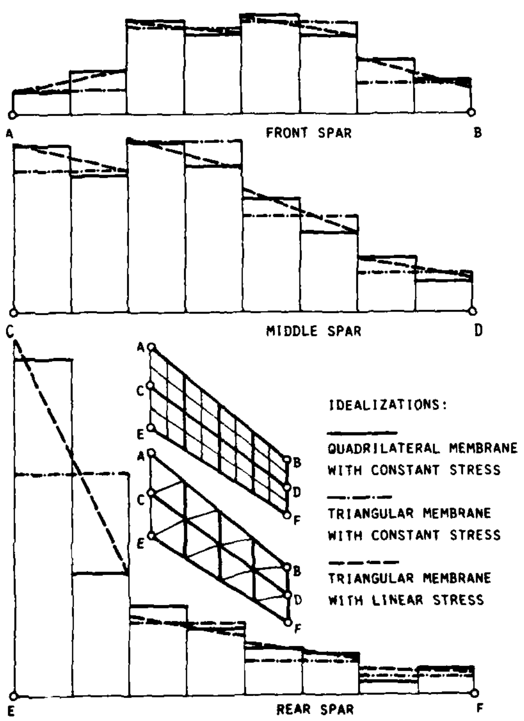


Fig. 11 STRESSES FOR DIFFERENT ELEMENT TYPES AND MESH SYSTEMS

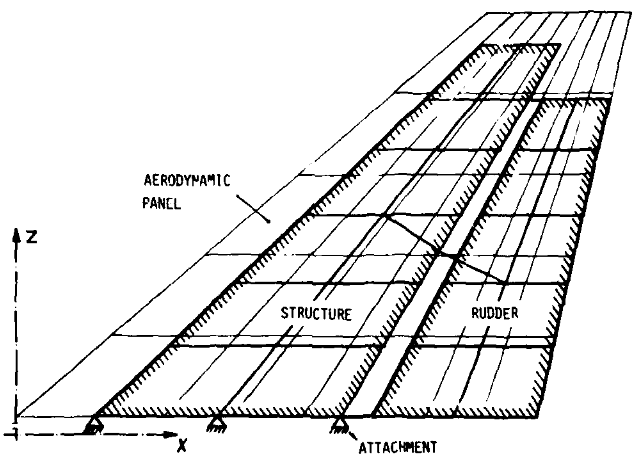


Fig. 12 IDEALIZATION OF A CFC-VERTICAL TAIL

AEROELASTIC EFFICIENCY CALCULATION FOR A CFC FIN AND RUDDER

For the structural design of fin and rudder, stiffness considerations are overriding and not strength. Also the size of these surfaces is influenced by their aeroelastic efficiency. The program ASAT was used to calculate the efficiency for a fin and rudder of a modern fighter plane. The aeroelastic deformations were calculated directly without using any iteration procedure which is possible because a full matrix of aerodynamic influence coefficients is produced by the aerodynamic module of ASAT.

The properties of CFC were introduced by the stress-strain law.

Fig. 12 shows the structural idealization for a CFC-fin and rudder. Fig. 13 shows the deflections of the structure due to a steady load case.

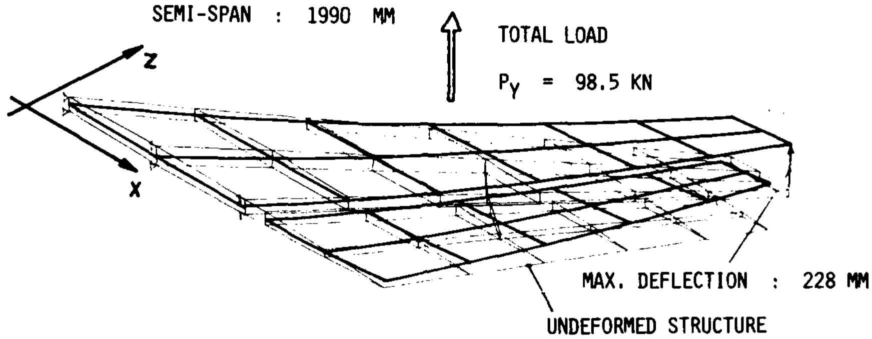


Fig. 13 DEFLECTION DUE TO A STATIC LOAD

Fig. 14 presents relatively large changes in the pressure distributions due to elastic fin deformations especially for the subsonic case.

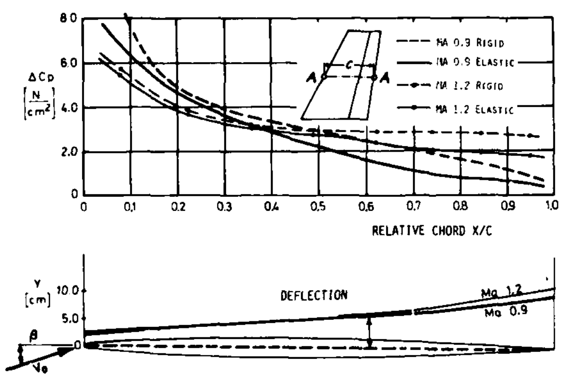


Fig. 14 PRESSURE DISTRIBUTIONS AND DEFORMATIONS AT SECTION A-A DUE TO A FIN ANGLE OF ATTACK β

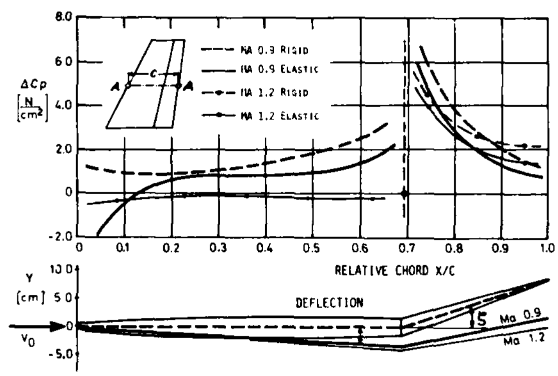


Fig. 15 PRESSURE DISTRIBUTIONS AND DEFORMATIONS AT SECTION A-A DUE TO A RUDDER ROTATION ANGLE ζ

Fig. 15 is depicting even larger effects on the fin pressure distribution due to rudder angle when elastic effects are considered.

Fig. 16 and Fig. 17 present the aeroelastic effectiveness of fin and rudder, and it is shown that the requirements which were postulated by the aerodynamic department can almost be fulfilled.

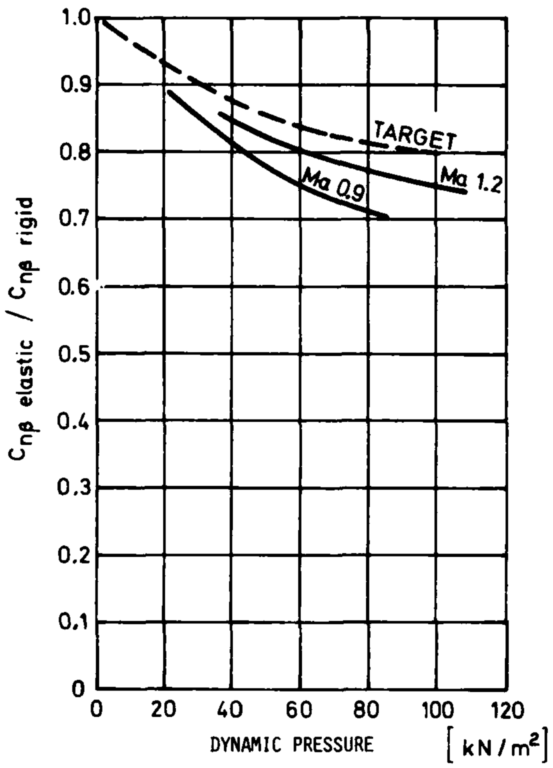


Fig. 16 VERTICAL TAIL AEROELASTIC EFFECTIVENESS

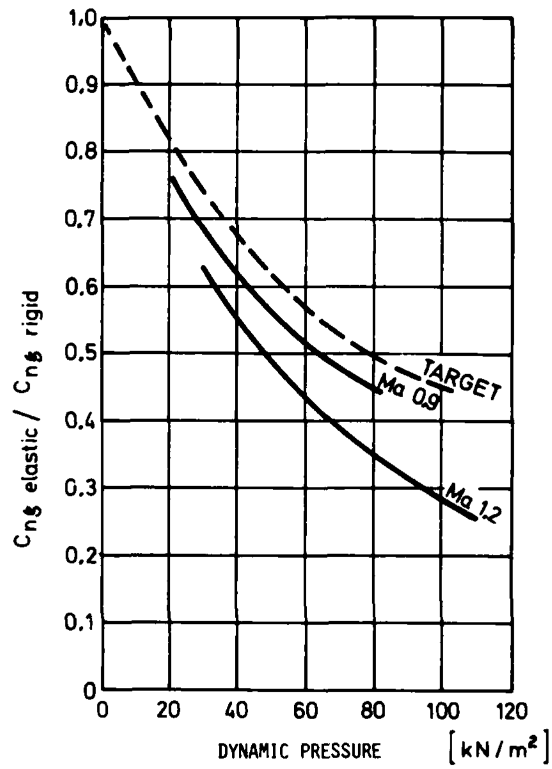


Fig. 17 RUDDER EFFECTIVENESS

STRUCTURAL OPTIMIZATION OF A CFC-DELTA-WING

For a preliminary design of a CFC-Delta-Wing, a structural optimization was performed to achieve a minimum weight structure by retaining sufficient control surface effectiveness. An additional constraint - a certain amount of wing twist off at a high g-manouvre - had to be fulfilled as well [5].

The direction of the laminates were selected in prestudies by the MBB-stress department which have accumulated a lot of experience with the CFC material over the last years [6].

Despite the fact that a huge amount of papers has been published lately about aeroelastic tailoring with CFC, it is our opinion that the possibilities for laying the laminates are limited for two major reasons:

- Material properties are only known for specific composites.
- Production considerations are dominating.

For these reasons, we took the preselected material properties [7] and fed it into the ASAT program as

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

The structure is practically idealized as a thin sandwich plate with the stress carrying capability in the skin. Deformation results for this model were compared with results calculated by the stress group who had a much finer grid, and good correlation was achieved.

Calculations were performed for the idealized structure of Fig. 18 and Fig. 19.

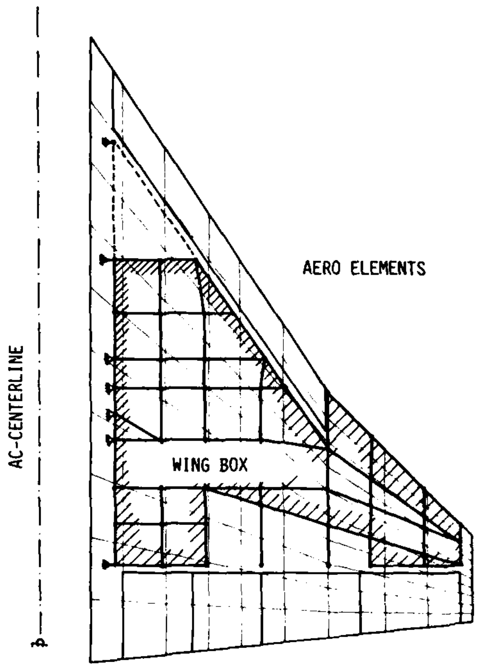


Fig. 18 IDEALIZED DELTA WING FOR STRUCTURAL DESIGN STUDIES

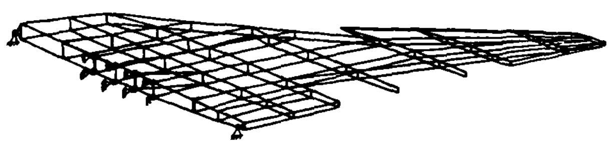


Fig. 19 WING BOX STRUCTURE

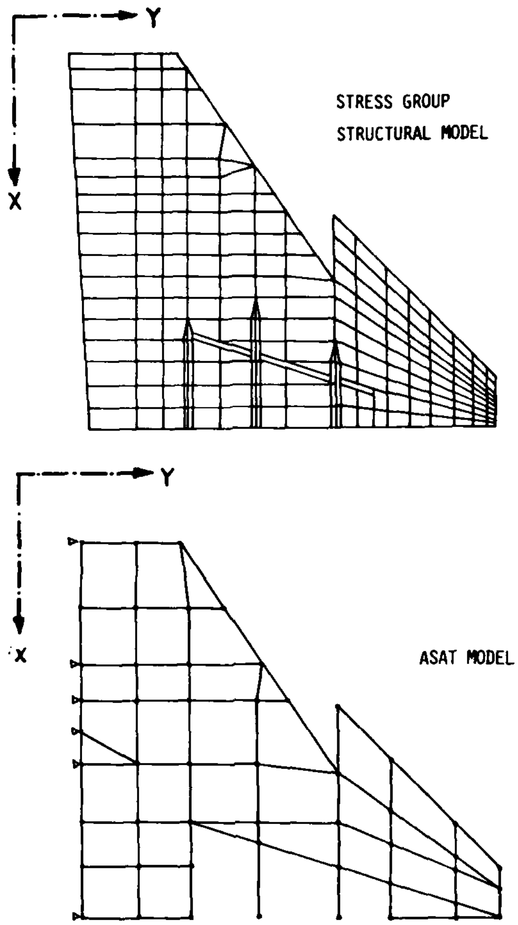


Fig. 20 COMPARISON OF DIFFERENT WING BOX IDEALIZATION

The structure is represented as follows:

Grid points:	106
Degrees of freedom:	278
Membranes:	74
Rod elements:	55
Shear panels:	67

The final result of these calcs were skin thicknesses adjusted to strength and buckling requirements and the effectivenesses for the control surfaces.

Fig. 20 shows the stress group grid and that one used by ASAT. Only from looking at these pictures, one can imagine that local stress concentrations - at attachments for instance - cannot be accounted for by the ASAT-idealization. For this reason, it is always necessary to follow up the optimization process with a normal stress analysis to confirm the results.

DETERMINATION OF LOADS

Two load cases were chosen according to the definitions of our loads group /8/:

Load case 1: Symmetrical high g pullout
This is a manouvre case in the subsonic regime giving the highest shear force and bending moment at the wing root.

Load case 2: This is a roll case in the supersonic flight regime were the aerodynamic center of pressure is backward. This case is not symmetrical (initiated by the ailerons) but was applied to both wings symmetrically.

In order to make the loads calculated by ASAT comparable to the loads from our loads group, the wing attitude and aileron angles are somewhat different - the presence of a canard had to be reflected which the ASAT program is not able to consider at the moment.

RESULTS OF DEFORMATION CALCULATIONS WITH ASAT AND COMPARISONS

After establishing the structural model and the loads, deformation calculations were performed which match the stress group results very well. Implicitly, this is also a prove that comparable loads were used. Fig. 21 shows the vertical deflection along the wing span for load case 1.

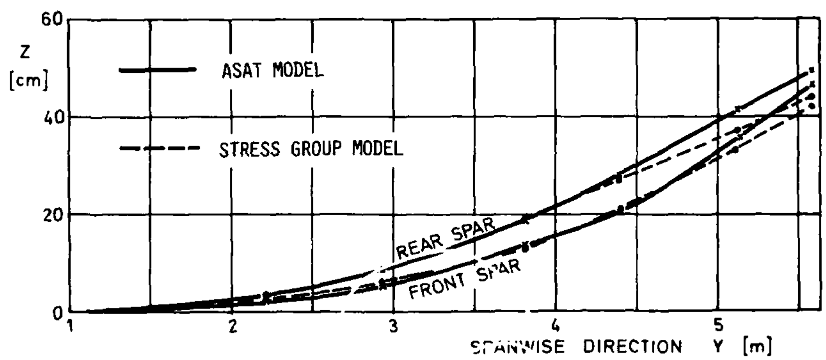


Fig. 21 COMPARISON OF WING DEFLECTIONS

In Fig. 22, the wing twist angle along the span is depicted. The 4° twist off angle at the wing tip fulfills the requirement coming from aerodynamic performance.

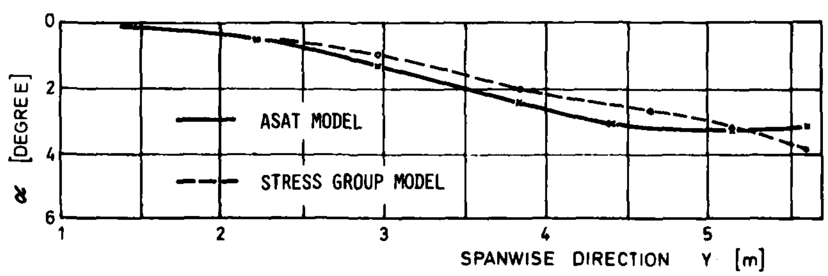


Fig. 22 COMPARISON OF WING TWIST ANGLE α

In Fig. 23, the internal skin load distribution for load case 1 is presented. From this figure, it can be deduced that extreme care must be taken to accomodate such high local forces into the two rear CFC attachments fitted to the fuselage.

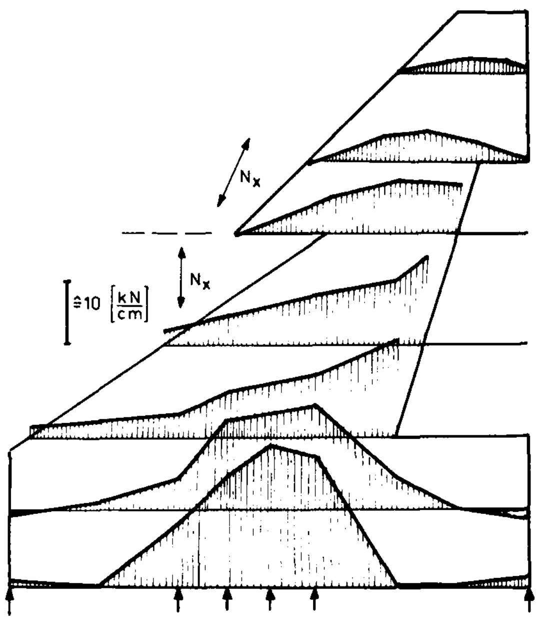


Fig. 23 INTERNAL SKIN LOAD DISTRIBUTION

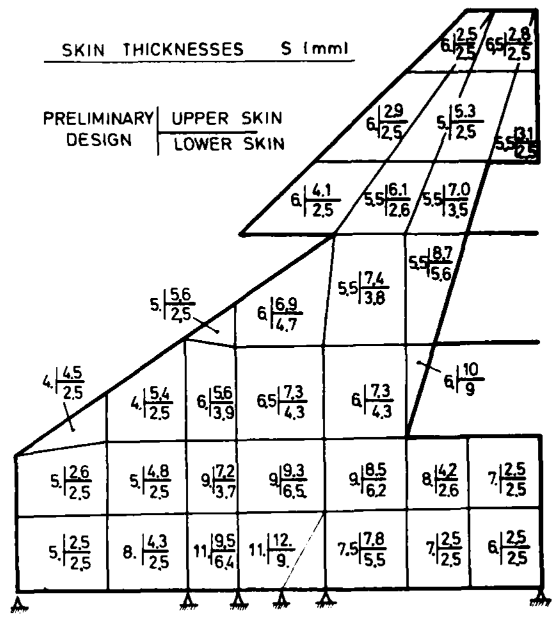


Fig. 24 WEIGHT OPTIMIZED SKIN THICKNESS ACCORDING TO STRENGTH CRITERIA (SUBSONIC AND SUPERSONIC LOAD CASES)

RESULTS OF THE OPTIMIZATION PROCESS

After three steps of the SOP program, the skin weight stayed almost constant. The final weight was

Step	Skin Weight [kg]
1	221.7
2	164.4
3	163.9
4	164.1

practically reached after the first step but the convergence had to be proven.

The weight saving amounts to about 5 % of the total wing weight which is a very considerable achievement.

Fig. 24 shows the skin thickness distributions before and after structural optimization.

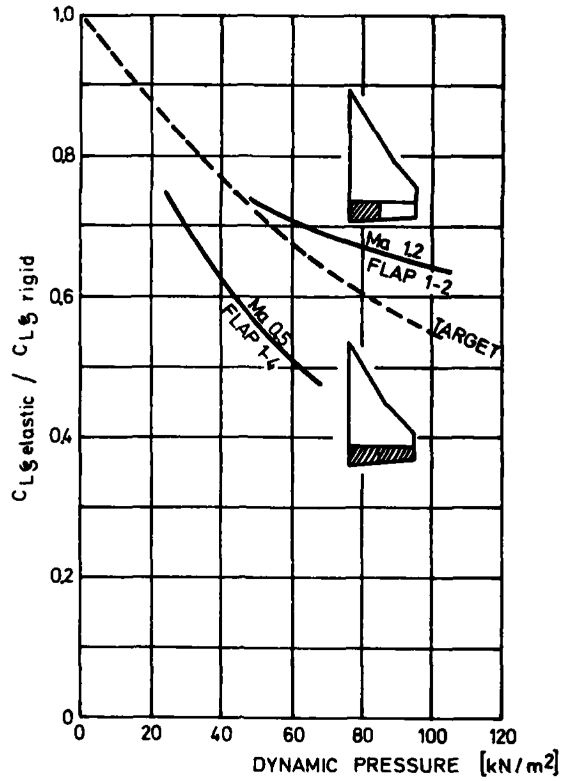


Fig. 25 WING-FLAP CONTROL EFFECTIVENESS

The aeroelastic efficiencies for the aileron are shown in Fig. 25 together with the effectiveness definition to fulfill the roll requirement. For the supersonic case where the roll manouvre is iniated with the two inner flaps only we have higher than required efficiency. For the subsonic pullout manouvre, the efficiency for all four flaps is somewhat below the requirement but it still is sufficient.

CONCLUSIONS

In this paper, it was shown that the very useful structural optimization program ASAT exists at MBB which was used for several practical design studies.

The major advantage of the system is that it merges several airplane designing disciplines such as:

- static loads
- stress calculations
- unsteady aerodynamics
- flutter calculations
- static aeroelastics
- weights

For this reason, communication errors are avoided.

Due to the versatility of the computer system, separate modules of it can be used solely, and it is also possible to make cross checks with results from other structural design groups. CFC structures can be treated efficiently, and the design goals postulated from aerodynamic performance could be reached.

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14. Abstract

A computer software system called ASAT exists at MBB which allows an automatic design of minimum weight structures. In this paper, the application of this system to several structures is described.

It is shown that a structural optimization system can be very useful in the preliminary design of an airplane, especially when it consists of several modules such as static load calculation, deformations and stress calculation by finite elements, static aeroelastics, weight calculation, unsteady aerodynamic forces, vibration calculation, flutter calculation, flutter and strength optimization which all can be used separately and independently.

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